APPARATUS AND METHOD FOR COMBINING MULTIPLE ELECTROMAGNETIC BEAMS INTO A COMPOSITE BEAM

BACKGROUND OF THE INVENTION

[1] Electronic color images, such as television images, are typically generated using three electromagnetic beams that each represent a different primary color. For example, a color-television screen typically includes an array of pixels that are each split into three phosphorescent regions: red (R), green (G), and blue (B). Three corresponding electron beams, one each for R, G, and B, are aligned such that they simultaneously strike the R, G, and B regions of the same pixels as the beams sweep across the screen. These beams cause the R, G, and B regions of a pixel to phosphoresce, and the human eye integrates the light generated by the phosphorescing R, G, and B regions of all the pixels to perceive a color image. By adjusting the respective intensities of the beams, the color television can generate a pixel having virtually any color. Alternatively, the R, G, and B beams can be light beams that the human eye perceives and integrates directly.

[2] **FIG. 1** is a diagram of an image generator ***100*** that scans a viewable color image onto a display area ***102*** of a retina or display screen using R, G, and B light beams ***104***, ***106***, and ***108***, which are aligned in a common horizontal plane. A scanning mirror ***110***, such as a microelectromechanical (MEM) mirror, sweeps the beams ***104***, ***106***, and ***108*** onto the area ***102*** to generate the image. Because the beams are horizontally aligned and separated by an angle θ, the contents of each beam is delayed relative to the other beams so that the beams form color pixels that are spatially aligned. For example, as the mirror ***110*** sweeps the beams from right to left, the B beam strikes a location P on the display area ***102***. As it strikes the location P, the B beam has the proper intensity for the blue component of the image pixel located at P. At some time later, the G beam strikes the location P. Therefore, the content of the G beam is delayed relative to the content of the B beam such that the G beam has the proper intensity for the green component of the pixel as it strikes the location P.

[3] A problem with the image generator ***100*** is that its maximum image scan angle Φ is 2*θ* less than the maximum image scan angle of a single-beam image generator (not shown). The maximum scan angle Φ is the angle over which the mirror ***110*** can scan an image onto the display area ***102***. Specifically, the rightmost portion of the area ***102*** is defined by the rightmost position of the B beam, *i.e.,* the position of the B beam when the mirror ***110*** is in its right most position. Likewise, the leftmost position of the area ***102*** is defined by the leftmost position of the R beam. When the B beam is in its rightmost position, and is thus at the rightmost edge of the area ***102***, the R beam is 2*θ* beyond the rightmost edge of the area ***102***. Likewise, when the R beam is in its leftmost position, and is thus at the leftmost edge of the area ***102***, the B beam is 2*θ* beyond the leftmost edge of the area ***102***. Consequently, 2*θ* of the sweep angle of the mirror ***110*** is wasted. That is, if the mirror ***110*** scanned only a single beam — the R beam for example — then Φ would increase by 2*θ*. This 2*θ* reduction in the maximum scan angle Φ may be significant in applications such as a virtual retinal display (VRD) where the maximum scan angle Φ of the mirror is small to begin with.

[4] To overcome the problem of a reduced scan angle in a multi-beam image generator such as the generator ***100***, one can combine the multiple beams into a single, composite beam.

[5] **FIG. 2** is a side view of a conventional beam combiner ***200***, often called an X-cube, which combines the R, G, and B light beams ***104***, ***106***, and ***108*** into a single composite beam ***202***. For clarity, the center rays of the R, G, and B beams are shown in solid line, and outer rays are shown in dash line. For purposes of illustration, the outer rays are presumed to be substantially parallel to the respective center rays.

[6] The X-cube ***200*** is a combination of four right-angle prisms ***204***, ***206***, ***208***, and ***210*** having vertices that meet at the center axis ***212*** (in the Z dimension) of the X-cube and form two interfaces ***214*** (dash line) and ***216*** (solid line). Before the X-cube ***200*** is assembled, the internal prism faces that form the first interface ***214*** are treated with an optical coating that reflects red light but passes green and blue light. Similarly, the prism faces that form the second interface ***216*** are treated with an optical

coating that that reflects blue light but passes green and red light. Furthermore, either before or after the X-cube ***200*** is assembled, the external faces ***218***, ***220***, ***222***, and ***224*** of the prisms ***204***, ***206***, ***208***, and ***210*** are polished to an optical finish since they respectively receive and project the R, G, B, and composite beams of light.

[7] First, the operation of the X-cube ***200*** is discussed where the R, G, and B beams ***104***, ***106***, and ***108*** include only their single center rays (solid line). This discussion also applies to thin beams — such as beams that are a single pixel wide — that are much narrower than the faces ***218***, ***220***, ***222***, and ***224*** of the X-cube ***200***. That is, this discussion also applies to collimated beams that are neither converging toward a focus nor diverging as they pass through the X-cube ***200***. The R, G, and B beams ***104***, ***106***, and ***108*** enter the X-cube ***200*** at the respective faces ***220***, ***218***, and ***222***, and the X-cube projects the composite beam ***202*** from the face ***222***. Specifically, the G beam ***106*** propagates through the face ***218*** to the center axis ***212***, passes through the interfaces ***214*** and ***216***, and exits the face ***222*** as part of the composite beam ***202***. The R beam ***104*** propagates through the face ***220*** to the center axis ***212***, and is reflected out of the face ***222*** by the interface ***214*** as part of the composite beam ***202***. Similarly, the B beam ***108*** propagates through the face ***224*** to the center axis ***212***, and is reflected out of the face ***222*** by the interface ***216*** as part of the composite beam ***202***. As long as the prisms ***204***, ***206***, ***208***, and ***210*** are properly dimensioned and aligned, the composite beam ***202*** is a single ray, *i.e.,* is no wider than the R, G, and B beams ***104***, ***106***, and ***108***.

[8] Therefore, referring to **FIG. 1**, one can use the X-cube ***200*** to increase the maximum scan angle of the image generator ***100***. Specifically, one can use the X-cube ***200*** to combine single-pixel R, G, and B beams ***104***, ***106***, and ***108*** into a composite beam that the scanning mirror ***110*** can sweep across an angle of $\Phi + 2\theta$ as discussed above in conjunction with **FIG. 1**.

[9] Next, the operation of the X-cube ***200*** is discussed where the R, G, and B beams ***104***, ***106***, and ***108*** are wider than a single ray (dashed line), *i.e.,* have diameters/widths that are on the order of the widths of the faces ***218***, ***220***, ***222***,

and ***224***. For example, such wide R, G, and B beams may respectively include the R, G, and B components of an entire image as opposed to merely a single pixel of the image. The operation is similar to that described above for the narrow-beam case, but because the R, G, and B beams are wider, they intersect the interfaces ***214*** and ***216*** at regions that are centered about the center axis ***212***. Furthermore, the interfaces ***214*** and ***216*** reverse the R and B beams such that the R and B image components in the composite beam ***202*** are the "mirror images" of the R and B image components in the R and B beams. But this reversal can easily be accounted for by "reversing" the contents of the R and B beams before they enter the X-cube ***200***.

[10] Image-projection devices, such as overhead projectors, often include an X-cube that operates in the wide-beam mode.

[11] Still referring to **FIG. 2**, a problem with the X-cube ***200*** is that the internal faces of each prism ***204***, ***206***, ***208***, and ***210*** typically must be precision machined and assembled to a high degree of flatness and angle accuracy to allow proper interfacing of the prisms. For example, the center vertex of each prism must be substantially a right angle (90°), and the internal prism faces must be polished to be substantially optically flat so that there are no gaps between the interfaces ***214*** and ***216***. Furthermore, because each prism has two internal faces that respectively form portions of the two interfaces ***214*** and ***216***, each prism must be twice treated with the respective optical coatings that produce the interfaces. In addition, each prism may be treated a third time with an anti-reflective coating on the respective external faces ***218***, ***220***, ***222***, and ***224***. Moreover, the prisms must be precisely aligned during assembly to insure even interfaces ***214*** and ***216***. Unfortunately, the precision machining, multiple treatments, and precision assembly typically make the X-cube ***200*** relatively complex and expensive to manufacture.

[12] Another problem is that for the X-cube ***200*** to function correctly, it may be necessary to rotate the polarization of the G beam ***106*** by 90° (relative to the polarization of the R and B beams) before it enters the X-cube. One way to accomplish this rotation is to insert a half-wave retarder (not shown) into the path of the G beam

before it enters the face ***218***. Unfortunately, this may increase the cost of an image generator that includes the X-cube.

Summary of the Invention

[13] In one aspect of the invention, a beam combiner includes a first beam-input face, a beam-output face, and first and second reflectors. The first beam-input face receives first and second beams of electromagnetic energy respectively having a first and second wavelengths. The first reflector reflects the first received beam toward the beam-output face, and the second reflector passes the first beam from the first reflector and reflects the received second beam toward the beam-output face. In one alternative, the first beam-input face also receives a third beam of electromagnetic energy having a third wavelength, the beam combiner includes a third reflector that reflects the received third beam toward the beam-output face, and the first and second reflectors pass the third beam from the third reflector. In another alternative, the beam combiner includes a second beam-input face that receives a third beam directed toward the beam-output face, and the first and second reflectors pass the third beam.

[14] Such a beam combiner can be less expensive than an X-cube because it is easier to manufacture. For example, the beam combiner often requires fewer precision cuts and has a less-stringent alignment tolerance because the most or all of the machining can be done after the combiner is assembled. Furthermore, the combiner can often be manufactured in bulk using off-the-shelf materials, thus further reducing the cost and manufacturing complexity.

[15] In addition, such a beam combiner does not require the use of a half-wave retarder.

Brief Description of the Drawings

[16] The foregoing aspects and many of the attendant advantages of this invention will become more readily appreciated as the same become better understood by reference to the following detailed description, when taken in conjunction with the accompanying drawings, wherein:

[17] **FIG. 1** is a diagram of an image generator that scans a color image using R, G, and B light beams.

[18] **FIG. 2** is a side view of a conventional X-cube that combines separate R, G, and B light beams into a single, composite light beam.

[19] **FIG. 3** is a side view of a beam combiner for combining separate R, G, and B light beams into a single, composite light beam and a diagram of an RGB beam source according to an embodiment of the invention.

[20] **FIG. 4** is side view of a beam combiner for combining separate R, G, and B light beams into a single, composite light beam according to another embodiment of the invention.

[21] **FIG. 5** is side view of a beam combiner for combining separate R, G, and B light beams into a single, composite light beam according to another embodiment of the invention.

[22] **FIG. 6** illustrates methods of manufacturing the beam combiners of **FIGS. 3 – 5** according to an embodiment of the invention.

[23] **FIG. 7** illustrates methods of mass producing the beam combiners of **FIGS. 3 – 5** according an embodiment of the invention.

[24] **FIG. 8** is a diagram of an image-beam generator that incorporates the beam combiner of **FIG. 5** according to an embodiment of the invention.

[25] **FIG. 9** is a diagram of an image generator that incorporates the image-beam generator of **FIG. 8** according to an embodiment of the invention.

DETAILED DESCRIPTION

[26] The following discussion is presented to enable a person skilled in the art to make and use the invention. The general principles described herein may be applied to embodiments and applications other than those detailed below without departing from the spirit and scope of the present invention. The present invention is not intended to

be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed or suggested herein.

[27] **FIG. 3** is a side view of a beam combiner ***300*** for combining separate R, G, and B light beams ***104***, ***106***, and ***108*** into a single, composite light beam ***302***, and a diagram of an RGB beam source ***304*** according to an embodiment of the invention. As discussed below, the combiner ***300*** is often easier and cheaper to manufacture than conventional combiners such as the X-cube ***200*** of **FIG. 2**.

[28] The beam combiner ***300*** includes three sections ***306***, ***308***, and ***310***, which are bonded together and which are made from a transparent material such as glass or polymer suitable for optical applications. The combiner ***300*** also includes an input face ***312*** having a length of 3W and a rectangular cross section in the X-Z plane, and includes an output face ***314*** having a height of W and a square cross section in the Y-Z plane. In one embodiment, W = 5.5 millimeters (mm), and in another embodiment W = 3.5 mm. Both the input face ***312*** and the output face ***314*** are flat, optical-quality surfaces. The manufacture of the combiner ***300*** is discussed below in conjunction with **FIGS. 6 – 7**.

[29] The first section ***306*** has a parallelogram-shaped cross section in the X-Y plane with a height and width of W and includes a segment input face ***316***, which forms part of the combiner input face ***312***, and a reflector face ***318*** for reflecting the R beam ***104*** toward the combiner output face ***314***. In one embodiment, the face ***318*** is made reflective by application of a conventional optical coating. One can select the reflective and transmissive properties of this coating (and the other coatings discussed below) according to the parameters of the beam-combiner system. The angle α between the input face ***316*** and the reflector face ***318*** is an acute angle. In a preferred embodiment, $\alpha = 45°$ to allow the R beam ***104*** to have a maximum width in the X dimension equal to W. That is, if $\alpha = 45°$, then all portions of a W-width R beam will project onto the reflector face ***318*** as long as the R beam is properly aligned with the input face ***316***. If, however, the combiner ***300*** is designed for a R beam ***104*** having a width less than W, then the region of the face ***318*** that is reflective can be limited to the

area that the R beam will strike. Alternatively the angle *α* can be made greater than 45°. But because the angle *α* is the same for all of the segments ***306***, ***308***, and ***310***, one should consider the effect on the other segments ***308*** and ***310*** before altering the value of *α*. Furthermore, if *α* does not equal 45°, then the angle of the R beam from the beam source ***304*** is adjusted such that the reflected R beam remains normal to the output face ***314***.

[30] Similarly, the second section ***308*** has a parallelogram-shaped cross section in the X-Y plane with a height and width of W and includes a segment input face ***320***, which forms part of the combiner input face ***312***, and includes a reflector face ***322***, which lies along an interface between the sections ***306*** and ***308*** and passes the reflected R beam ***104*** and reflects the G beam ***106*** toward the combiner output face ***314***. In one embodiment, the face ***322*** is made reflective by application of a conventional optical coating to either or both the face ***322*** and the face of the section ***306*** that interfaces with the face ***322***. The angle *α* between the input face ***320*** and the reflector face ***322*** is an acute angle, and is preferably equal to 45° to allow the G beam ***106*** to have a maximum width in the W dimension equal to W. If, however, the combiner ***300*** is designed for a G beam ***106*** having a width less than W, then the region of the face ***322*** that is reflective can be limited to the area that the G beam will strike. Alternatively the angle *α* can be made greater than 45°. But because the angle *α* is the same for all of the segments ***306***, ***308***, and ***310***, one should consider the effect on the other segments ***306*** and ***310*** before altering the value of *α*. Furthermore, if *α* does not equal 45°, then the angle of the G beam from the beam source ***304*** is adjusted such that the reflected G beam remains normal to the output face ***314***.

[31] The third section ***310*** has a triangular-shaped cross section in the X-Y plane and includes the combiner output face ***314***, a segment input face ***324***, which has a width of W and which forms part of the combiner input face ***312***, and a reflector face ***326***, which lies along an interface between the sections ***308*** and ***310*** and passes the reflected R and G beams ***104*** and ***106*** and reflects the B beam ***108*** toward the combiner output face. In one embodiment, the face ***326*** is made reflective by application of a conventional optical coating to either or both the face ***326*** and the face

of the section ***308*** that interfaces with the face ***326***. The angle α between the input face ***324*** and the reflector face ***326*** is an acute angle, and is preferably equal to 45° to allow the B beam ***108*** to have a maximum width in the X-dimension equal to W. If, however, the combiner ***300*** is designed for a B beam ***108*** having a width less than W, then the region of the face ***326*** that is reflective can be limited to the area that the B beam will strike. Alternatively the angle α can be made greater than 45°. But because the angle α is the same for all of the segments ***306***, ***308***, and ***310***, one should consider the effect on the other segments ***306*** and ***308*** before altering the value of α. Furthermore, if α does not equal 45°, then the angle of the B beam from the beam source ***304*** is adjusted such that the reflected B beam is normal to the output face ***314***. Moreover, an angle β between the section input face ***324*** and the output face ***314*** is substantially a right angle in a preferred embodiment.

[32] The beam source ***304*** includes three beam-generating sections ***328***, ***330***, and ***332*** for respectively generating the R, G, and B beams such that they traverse paths having substantially the same optical length. This causes the images of the R, G, and B light-emitting points in the combined beam to occur at the same distance from the output face ***314*** of the beam combiner ***300***, and thus allows focusing of all three colors to the same plane with a single focusing lens located after the output face of the beam combiner. For purpose of illustration, assume that the center rays (shown in solid line) of the R, G, and B beams enter the respective centers (in the X dimension) of the faces ***316***, ***320***, and ***324*** as shown in **FIG. 3**, and that the beam combiner ***300*** and the medium between the beam combiner and the beam source ***304*** have respective indices of refraction equal to one. Consequently, the R-beam center ray strikes and is reflected from the center (in the Y dimension) of the face ***318***, and the reflected R-beam propagates through the centers (in the Y dimension) of the faces ***322***, ***326***, and ***314***. Using known geometrical principles, the length of the path traversed by the R-beam center ray from the section ***328*** to the face ***314*** equals D + 3W — 1/2W from the face ***316*** to the face ***318***, 2W from the face ***318*** to the face ***326***, and 1/2W from the face ***326*** to the face ***314*** — where $D \geq 0$. By respectively locating the beam-generator sections ***330*** and ***332*** W and 2W farther away from the combiner input face ***312*** than the section

328 is, the lengths of the paths traversed by the G- and B-beam center rays to the output face ***314*** are set to the same optical length D + 3W. Moreover, using known geometrical principles, one can show that the outer rays (not shown in **FIG. 3**) of the R, G, and B beams also traverse the same optical path length D + 3W. Consequently, all rays of the R, G, and B beams will traverse the same optical path length even if the center rays (solid line) of the beams are not respectively aligned with the centers of the segment-input faces ***316***, ***320***, and ***324***.

[33] Although the preceding discussion approximates optical path length as actual path length, one of skill in the art will realize that the optical path length through a medium other than free space is typically longer than the actual path length due to the medium having an index of refraction that is greater than one. Consequently, one can more precisely equalize the optical path lengths that the R, G, and B beams traverse by accounting for the indices of refraction of the segments ***306***, ***308***, and ***310*** and the medium between the beam combiner and the beam source ***304*** when determining the respective distances between the beam-generating sections ***328***, ***330***, and ***332*** and the input face ***312***.

[34] Moreover, the beam source ***304*** is preferably aligned with the beam combiner ***300*** such that the center rays (solid line) of the R, G, and B beams ***104***, ***106***, and ***108*** are respectively aligned with the centers (in the X dimension) of the section input faces ***316***, ***320***, and ***324***. However, even if the center rays are not aligned with the face centers, the R, G, and B beams will be aligned such that, in the composite beam ***302***, the center rays of all three beams will be approximately collinear.

[35] Still referring to **FIG. 3**, the operation of the beam combiner ***300*** is discussed according to an embodiment of the invention. For purpose of illustration, optical path length is approximated as actual path length in the following discussion. But as discussed above, one of ordinary skill in the art would be able to more precisely equalize the optical paths traversed by the R, G, and B beams by accounting for the indices of refraction along those paths.

[36] The R beam ***104*** propagates the distance D from the beam-generating section ***328*** to the beam-input face ***316***, and is substantially normal to the beam-input face. Preferably, the center ray of the R beam is aligned with the center of the face ***316*** in the X dimension. Next, the R beam propagates the distance W/2 from the face ***316*** to the reflector ***318***. Then, the reflected R beam, which is substantially parallel to the face ***316***, propagates the distance 2W from the reflector ***314*** to the reflector ***326***, and then propagates another W/2 to the beam-output face ***314*** as part of the composite beam ***302***, which is substantially normal to the beam-output face. Therefore, as stated above, the optical length of the R-beam path from the beam-generator section ***328*** to the beam-output face ***314*** is D + 3W.

[37] The G beam ***106*** propagates the distance W + D from the beam-generating section ***330*** to the beam-input face ***320***, and is substantially normal to the beam-input face. Preferably, the center ray of the G beam is aligned with the center of the face ***320*** in the X dimension. Next, the G beam propagates the distance W/2 from the beam-input face ***320*** to the reflector ***322***. Then, the reflected G beam, which is substantially parallel to the face ***320*** and substantially coincident with the reflected R beam ***104***, propagates the distance W from the reflector ***322*** to the reflector ***326***, and then propagates another W/2 to the beam-output face ***314*** as part of the composite beam ***302***. Therefore, as stated above, the optical length of the G-beam path from the beam-generator section ***330*** to the beam-output face ***314*** is D + 3W.

[38] The B beam ***108*** propagates the distance 2W +D from the output of the beam-generating section ***332*** to the beam-input face ***324***, and is substantially normal to the beam-input face. Preferably, the center ray of the B beam is aligned with the center of the face ***324*** in the X direction. Next, the B beam propagates the distance W/2 from the beam-input face ***324*** to the reflector ***326***. Then, the reflected B beam which is substantially parallel to the face ***324*** and substantially coincident with the reflected R and G beams, propagates a distance of W/2 from the reflector ***326*** to the beam-output face ***314*** as part of the composite beam ***302***. Therefore, as stated above, the optical length of the B-beam path from the beam-generator section ***332*** to the beam-output face ***314*** is D + 3W.

[39] Still referring to **FIG. 3**, if the composite beam ***302*** is an image beam, *i.e.,* includes the R, G, and B components of an entire image, then the R, G, and B beams respectively include the instantaneous red, green, and blue components of the image. One can use an optional optical assembly (not shown in **FIG. 3**) to project the composite beam, and thus the image, onto a display screen (not shown in **FIG. 3**).

[40] Alternatively, if the composite beam ***302*** is a pixel beam, *i.e.,* includes the R, G, and B components of a single pixel, then the R, G, and B beams respectively include the instantaneous red, green, and blue components of the pixel. One can use a scanner such as the scanning mirror ***110*** of **FIG. 1** to generate an image by sweeping the composite beam across a display screen (not shown in **FIG. 3**).

[41] Alternate embodiments of the beam combiner ***300*** and beam source ***304*** are contemplated. In one such embodiment, the R, G, and B beams may enter the input face ***312*** of the beam combiner ***300*** in an order other than the order (R-G-B) shown. For example, instead of the beam-generator section ***328*** generating the R beam and the beam-generator section ***332*** generating the B beam, the section ***328*** can generate the B beam and the section ***332*** can generate the R beam such that the R and B beams enter the combiner sections ***310*** and ***306***, respectively. Where the beams do not enter the input face ***312*** in the same order in which they appear in the electromagnetic spectrum (RGB or BGR), the reflective coatings that form the reflectors ***318***, ***322***, and ***326*** are more complex, requiring a band-pass response instead of a low- or high-pass response . Furthermore, the input face ***312*** may have other than a rectangular cross section, and the output face may have other than a square cross section. Moreover, one of the sections ***306*** or ***308*** may be omitted so that the combiner ***300*** generates the composite beam ***302*** from only two beams, such as R and B, R and G, or G and B. In addition, one can add additional sections that are similar to the sections ***306*** and ***308*** so that the combiner ***300*** generates the composite beam ***302*** from more than three beams. Furthermore, the widths of the segment input faces ***316***, ***320***, and ***324*** need not be equal. But to allow transfer of all the energy in the R, G, B beams to the combined beam ***302*** in this situation, the widths of the beams ***104***, ***106***, and ***108*** where they enter the respective segment input faces ***316***, ***320***, and ***324*** are

typically no greater than the widths of the respective segment input faces. Moreover, where the width of the face ***324*** is greater than the width of the face ***320***, the segment ***310*** has a truncated triangular shape (flat bottom). In addition, although the segment input faces ***316***, ***320***, and ***324*** are shown as being coplanar to form a planar input face ***312***, the segment input faces need not be coplanar, and thus the input face ***312*** need not be planar. For example, the segment input face ***316*** may extend further toward, or abut, the beam-generator section ***328***. Similarly, the segment input face ***320*** may extend further toward, or abut, the beam-generator section ***330***, and the segment input face ***324*** may extend further toward, or abut, the beam-generator section ***332***. Depending on the system parameters, this may reduce the distance between the beam combiner ***300*** and the beam source ***304***, and thus may reduce the overall size of a module that includes the combination of the beam combiner and beam source. Furthermore, extending the segment input faces ***316***, ***320***, and ***324*** such that they respectively abut (or nearly abut) the beam-generator sections ***328***, ***330***, and ***332*** inherently equalizes the optical path lengths because the R, G, and B beams are propagating through only one material having a single index of refraction before emerging from the output face ***314***.

[42] **FIG. 4** is a side view of a beam combiner ***400*** for combining separate R, G, and B light beams ***104***, ***106***, and ***108*** (only center rays shown in **FIG. 4**) into a single, composite light beam ***402*** according to another embodiment of the invention. As discussed above in conjunction with **FIG. 3**, optical path length is approximated as actual path length in the following discussion. The combiner ***400*** is similar to the combiner ***300*** of **FIG. 3** except that it allows the optical path lengths of the R, G, and B beams to be reduced. These reduced optical path lengths also allow the combiner ***400*** to receive R, G, and B beams having larger numerical apertures, and allow a reduction in the size of a module that includes the combiner ***400*** and a beam source (omitted from **FIG. 4** for clarity). In one embodiment, the beam source is the same as the beam source ***304*** of **FIG. 3** but is located closer to the beam combiner ***400*** than it is to the combiner ***300***.

[43] The beam combiner ***400*** includes three sections ***406***, ***408***, and ***410*** that are bonded together and that are made from a transparent material such as glass or polymer suitable for optical applications. The combiner ***400*** includes an input face ***412***, which is also the input face of the section ***410***, and which has a length W and a square cross section in the X-Z plane, and includes an output face ***414*** having a height W and a square cross section in the Y-Z plane. Both the input face ***412*** and the output face ***414*** are flat optical-quality surfaces. The manufacture of the combiner ***400*** is discussed below in conjunction with **FIGS. 6 – 7**.

[44] The first section ***406*** has a parallelogram-shaped cross section in the X-Y plane, a width of S in the X dimension, and includes a reflector face ***418*** for reflecting the R beam toward the combiner output face ***414***. Because S is significantly smaller than the width W of the segment ***306*** of **FIG. 3**, the optical path length of the R beam can be made significantly smaller than 3W + D as discussed below. In one embodiment, the face ***418*** is made reflective by application of a conventional optical coating.

[45] Similarly, the second section ***408*** has a parallelogram-shaped cross section in the X-Y plane, a width of S in the S dimension, and includes a reflector face ***422***, which lies along an interface between the sections ***406*** and ***408*** and which passes the reflected R beam and reflects the G beam toward the combiner output face ***414***. Again, because S is significantly smaller than the width W of the segment ***308*** of **FIG. 3**, the optical path length of the G beam can be made significantly smaller than 3W + D as discussed below. In one embodiment, the face ***422*** is made reflective by application of a conventional optical coating to either or both the face ***422*** and the face of the section ***406*** that interfaces with the face ***422***.

[46] Like the third section ***310*** of **FIG. 3**, the third section ***410*** has a triangular-shaped cross section in the X-Y plane and includes the combiner input and output faces ***412*** and ***414*** and a reflector face ***426***, which lies along an interface between the sections ***408*** and ***410*** and which passes the reflected R and G beams and reflects the B beam toward the output face ***414***. In one embodiment, the face ***326*** is

made reflective by application of a conventional optical coating to either or both the face ***426*** and the face of the section ***408*** that interfaces with the face ***426***. The angle α between the input face ***412*** and the reflector face ***326*** is an acute angle, and is preferably equal to 45°. But if α does not equal 45°, then the angle of the B beam incident to the face ***412*** is adjusted such that the reflected B beam remains normal to the output face ***414***. Furthermore, the angle β between the section input face ***324*** and the output face ***314*** is a right angle in a preferred embodiment.

[47] Using known geometrical principles, the length of the path traversed by the R-beam center ray from the beam generator (not shown in **FIG. 4**) ***328*** to the face ***414*** equals D + T + 2S +U = D + 2S + W (where W = T + U). So that the center rays of both the G and B beams traverse the same path length, the G and B beam-generator sections (not shown in **FIG. 4**) are respectively placed D + S and D + 2S away from the beam input face ***412***. Where S is smaller than W, the common optical path length for the combiner ***400*** is less than the common optical path length of the combiner ***300*** of **FIG. 3**. That is, D + 2S + W < D + 3W where S < W. Consequently, the level of beam aberration associated with the combiner ***400*** can be significantly less than that associated with the combiner ***300***. Furthermore, one can select a value of S and position the R, G, and B beams such that the composite beam ***402*** exits the center of the beam output face ***414*** in the Y dimension, *i.e.,* U = T = W/2.

[48] Because the R beam passes through the B and G reflector faces ***422*** and ***426*** before striking the R reflective face ***418***, and because the G beam passes through the B reflector face ***426*** before striking the G reflective face ***422***, the spectra of the R and G beams and the faces ***422*** and ***426*** are non overlapping so that the combiner ***400*** does not generate artifacts such as "ghost" images. Specifically, if the face ***422*** or ***426*** reflects any of the R beam, or if the face ***426*** reflects any of the G beam (such reflections are shown in dashed line), then one or more unwanted beams ***428*** (dashed line) will emanate from the beam output face ***414*** in addition to the composite beam ***402***. These unwanted beams ***428*** may cause unwanted artifacts in the generated image. Consequently, it is preferred that the R beam contain no wavelengths that are

within the spectrum of wavelengths that the faces ***422*** and ***426*** reflect, and that the G beam contain no wavelengths that are within the spectrum of wavelengths that the face ***426*** reflects. One technique for accomplishing this is to tune the beam generator (not shown in **FIG. 4**) such that the R and G beams contain no such unwanted wavelengths. Another technique is to filter such unwanted wavelengths from the R and G beams before they enter the combiner ***400***.

[49] In another embodiment, the level of artifacts such as "ghost" images is reduced or eliminated by making S large enough so that the unwanted beams ***428*** of the R and G beams are sufficiently spaced from the composite beam ***402***.

[50] Furthermore, if the R beam (or a portion thereof) incident on the input face ***412*** is shifted to the left such that the beam is not incident on the face ***426***, then the R beam (or portion thereof) does not generate a corresponding unwanted beam ***428***. Likewise, if the R beam (or a portion thereof) is shifted further to the left such that it is not incident on the face ***422***, then the R beam (or portion thereof) does not generate unwanted beams ***428*** corresponding to the faces ***422*** and ***428***. A similar analysis applies to the G beam.

[51] Still referring to **FIG. 4**, the operation of the beam combiner ***400*** is similar to the operation of the beam combiner ***300*** as discussed above in conjunction with **FIG. 3**.

[52] Alternate embodiments of the beam combiner ***400*** are contemplated. In one such embodiment, the R, G, and B beams may enter the input face ***412*** of the beam combiner ***400*** in an order other than the order (R-G-B) shown. For example, instead of the B beam entering the combiner ***400*** closest to the output face ***414***, one may swap the positions of the R and B beams. Furthermore, the ends of the sections ***406*** and ***408*** need not be coplanar with the input face ***412***. Conversely, the R or G beams may be incident on the sections ***406*** and ***408*** instead of on the section ***410***. Moreover, one of the segments ***406*** or ***408*** may be omitted so that the combiner ***400*** generates the composite beam ***402*** from only two beams. In addition, one can add additional sections that are similar to the sections ***406*** and ***408*** so that the combiner ***400***

generates the composite beam ***402*** from more than three beams. Furthermore, the input face ***412*** may have other than a rectangular cross section, and the output face ***414*** may have other than a square cross section.

[53] **FIG. 5** is a side view of a beam combiner ***500*** for generating a composite beam ***502*** according to another embodiment of the invention. As discussed above in conjunction with **FIGS. 3** and **4**, optical path length is approximated as actual path length in the following discussion. The combiner ***500*** is similar to, but smaller than, the beam combiner ***300*** of **FIG. 3**. The reduced optical path lengths in the combiner ***500*** allow the combiner to receive R, G, and B beams having larger numerical apertures, and allow a reduction in the size of a module that includes the combiner and a beam source (omitted from **FIG. 5**). Furthermore, the combiner ***500*** has fewer reflective faces than the comber ***300***, and thus may be easier and less expensive to manufacture.

[54] The beam combiner ***500*** includes three sections ***506***, ***508***, and ***510*** that are bonded together and that are made from a transparent material such as glass or polymer suitable for optical applications. The combiner ***500*** includes two input faces ***512*** and ***514*** having a length 2W and a height W, respectively, and includes an output face ***516*** having a height W. The input face ***512*** has a rectangular cross section in the X-Z plane, and the input face ***514*** and the output face ***516*** each have a square cross section in the Y-Z plane. The input faces ***512*** and ***514*** and the output face ***516*** are flat optical-quality surfaces. The manufacture of the combiner ***500*** is discussed below in conjunction with **FIGS. 6 – 7**.

[55] The first section ***506***, which effectively replaces the section ***306*** of **FIG. 3**, has a triangular-shaped cross section in the X-Y plane and includes the combiner input face ***514***, which receives the R beam ***104***, and has an angle $\beta 1$, which is preferably a right angle.

[56] The second section ***508*** and the third section ***510*** are similar or identical to the second and third sections ***308*** and ***310*** of **FIG. 3**. The second section ***508*** includes a segment input face ***518***, which forms part of the second combiner input face ***512***, and includes a reflector face ***520***. The third section ***510*** includes the combiner output

face ***516***, a segment input face ***522***, which forms part of the combiner input face ***512***, and a reflector face ***524***.

[57] Referring to **FIGS. 3** and **5**, by replacing the parallelogram section ***306*** with the triangular section ***506*** and receiving the R beam via the input face ***514*** instead of the input face ***512***, the combiner ***500*** can allow a reduction in the aberration of the composite beam ***502***. Specifically, the path of the R beam through the combiner ***500*** is 2W, which is 33% shorter than the R-beam path (3W) through the combiner ***300***. Consequently, by placing the R beam-generating section ***328*** of the beam generator ***304*** a distance D from the input face ***514***, and by placing the G and B sections ***330*** and ***332*** respective distances D and D + W from the input face ***512***, one can reduce the optical path lengths of the R, G, and B beams to D + 2W, and thus reduce the aberration of the composite beam ***502***. Furthermore, reducing the distance between the beam generator ***304*** and the combiner ***500*** allows for a more compact image-beam generator as discussed below in conjunction with **FIG. 8**.

[58] The operation of the beam combiner ***500*** is similar to the operation of the beam combiner ***300*** of **FIG. 3**.

[59] Alternate embodiments of the beam combiner ***500*** are contemplated. In one such embodiment, the R, G, and B beams may enter the input faces ***512*** and ***514*** of the beam combiner ***500*** in an order other than the order (R-G-B) shown. For example, instead of the input face ***514*** receiving the R beam and the input face ***522*** receiving the B beam, the input face ***514*** can receive the B beam and the input face ***522*** can receive the R beam. Furthermore, the cross section of the input face ***512*** may be other than rectangular, and the cross sections of the faces ***514*** and ***516*** may be other than square. Moreover, one can omit the section ***508*** so that the combiner ***500*** generates the composite beam ***502*** from only two beams. In addition, one can add additional sections that are similar to the section ***508*** so that the combiner ***500*** generates the composite beam ***502*** from more than three beams.

[60] As an alternative, the beam combiner may be assembled such that input faces **518** and **522** are not coplanar, but rather are parallel planes. For example, face

522 may be raised by a distance W toward the blue light source. This results in a beam combiner that provides inherent optical path length equalization.

[61] **FIG. 6** illustrates a method for manufacturing the beam combiners ***300***, ***400***, and ***500*** of **FIGS. 3 - 5** according to an embodiment of the invention.

[62] First, one conventionally coats the surfaces of transparent slabs ***600***, ***602***, and ***604*** with the desired wavelength-sensitive reflective optical coatings as discussed above in conjunction with **FIGS. 3 - 5**. One can typically obtain optical-quality slabs of glass or other transparent material "off the shelf" from optical suppliers. Therefore, one typically need not polish the surfaces of the slabs ***600***, ***602***, or ***604*** before applying the optical coatings. Furthermore, to form the combiner ***300*** of **FIG. 3** or the combiner ***500*** of **FIG. 5**, all of the slabs typically have the same thickness, although this is not a requirement. To form the combiner ***400*** of **FIG. 4**, however, the slabs ***600*** and ***602*** typically have the same thickness but are thinner than the slab ***604***.

[63] Next, one bonds the optically coated slabs ***600***, ***602***, and ***604*** together using a conventional optical adhesive.

[64] Then, one cuts the bonded slabs along the appropriate dashed cut lines to form the combiner. To form the combiner ***300*** of **FIG. 3**, one cuts the slabs ***600***, ***602***, and ***604*** along the lines ***606***, ***608***, and ***610***. To form the combiner ***400*** of **FIG. 4**, one cuts the slab ***604*** along the lines ***606*** and ***608***. If no beams will enter the slabs ***600*** or ***602***, one need not cut through the slabs ***600*** and ***602*** along the lines ***606*** and ***610***, although one may do so. And to form the combiner ***500*** of **FIG. 5**, one cuts the slabs ***600***, ***602***, and ***604*** along the lines ***606***, ***608***, ***610***, and ***612***. In all cases, one also cuts the slabs along a line (not shown) to give the combiner the desired depth in the Z dimension. One can use any conventional tool or technique, such as water-jet or laser technology, to cut the slabs.

[65] Next, one conventionally polishes the beam-receiving and beam-projecting surfaces of the cut slabs to an optical-quality finish. For example, to form the combiner ***300*** (**FIG. 3**), one polishes the surfaces formed by the cuts along the lines ***606*** and ***608***.

[66] Although one can cut and polish the slabs before bonding them together, this may increase the manufacturing complexity and cost because one must properly align the cut and polished pieces before bonding.

[67] **FIG. 7** illustrates a method for manufacturing the beam combiners ***300***, ***400***, and ***500*** of **FIGS. 3 – 5** according to another embodiment of the invention. Unlike the method of **FIG. 6**, this method allows the simultaneous manufacture of multiple combiners from the same slabs. This mass production often reduces the per-combiner manufacturing complexity and cost.

[68] First, one conventionally coats the surfaces of three or more transparent slabs. The example of **FIG. 7** shows ***700***, ***702***, ***704***, ***706***, and ***708*** with the desired wavelength-sensitive reflective optical coatings as discussed above in conjunction with **FIGS. 3 - 5**. The slabs ***700***, ***702***, and a first portion of the slab ***704*** will form a first group of combiners, and the slabs ***706***, ***708***, and a second portion of the slab ***704*** will form a second group of combiners as described below. For example, to form combiners ***300*** (**FIG. 3**), one applies a red-reflecting coating to the faces ***710*** and ***712*** of the slabs ***700*** and ***708***, a green-reflecting/red-passing coating to the faces ***714*** and ***716*** of the slabs ***702*** and ***706***, and a blue-reflecting/red-and-green-passing coating to the faces ***718*** and ***720*** of the slab ***704***. As stated above in conjunction with **FIG. 6**, these slabs typically have optical-quality surfaces, so one need not polish the surfaces of the slabs before applying the optical coatings. Furthermore, to form the combiner ***300*** of **FIG. 3** or the combiner ***500*** of **FIG. 5**, all of the slabs typically have the same thickness. To form the combiner ***400*** of **FIG. 4**, however, the slabs ***700***, ***702***, ***706***, and ***708*** typically have the same thickness but are thinner than the slab ***704***.

[69] Next, one bonds the optically coated slabs ***700***, ***702***, ***704***, ***706***, and ***708*** together using a conventional optical adhesive. The ends of the slabs are staggered as shown to maximize the number of combiners that can be formed.

[70] Then, one cuts the bonded slabs along the horizontal lines ***722a*** – ***722h*** to form individual plates ***724a*** - ***724g***. At this point, one can, but does not need to, polish

the tops and bottoms of the plates (the optically coated sides have already been polished) to an optical-quality finish, as discussed above.

[71] Next, one cuts the plates ***724a*** - ***724g*** in half along the vertical lines ***726a - 726g***.

[72] Then, to form either combiners ***300*** (**FIG. 3**) or ***400*** (**FIG. 4**), one polishes the appropriate surfaces of the resulting half plates. For example, to form combiners ***300*** (**FIG. 3**), one polishes the top (along cut ***722a***) and side (along cut ***726a***) surfaces of the left half of the plate ***724a*** to respectively form the input faces ***312*** and the output faces ***314*** (**FIG. 3**). Then one cuts the polished half plates along one or more vertical planes (not shown) that are parallel to the X-Y plane to form the combiners ***300*** or ***400***. For example, if the half plates have depths of ten centimeters (cm) in the Z dimension and one wants combiners ***300*** that are one cm thick in the Z dimension, then one cuts the half plates at one cm intervals in the Z dimension along planes that are parallel to the X-Y plane. Because the surfaces formed by these cuts neither receive nor emanate light beams, they need not be polished.

[73] To form the combiners ***500*** (**FIG. 5**), one cuts the half slabs along the lines ***728a*** - ***728g*** and ***730a*** - ***730g***. Then, one polishes the appropriate surfaces of the cut half plates. For example, to form one or more combiners ***500*** from the left half of the plate ***724a***, one polishes both end surfaces (along cut lines ***726a*** and ***728a***) and the top surface (along the cut line ***722a***) to an optical-quality finish. Then one cuts the polished half plates in the Z dimension along one or more vertical planes (not shown) that are parallel to the X-Y plane to form the combiners ***500*** in a manner similar to that discussed in the preceding paragraph.

[74] Referring to **FIGS. 6** and **7**, alternate embodiments of the described manufacturing methods are contemplated. For example, one can perform the cutting, polishing, and bonding steps in any order that yields the desired beam combiner or combiners. Furthermore, one can apply the reflective optical coatings to opposite surfaces of the same interface. For example, instead of applying the green-reflecting/red-passing coating to the faces ***714*** and ***716*** of the slabs ***702*** and ***706***,

one can apply this coating to the respective abutting faces of the slabs ***700*** and ***708***. Or one can apply the coating to both the faces ***714*** and ***716*** and to the respective abutting faces of the slabs ***700*** and ***708***. In addition, one can add additional pairs of transparent slabs to increase the number of combiners yielded by each plate ***724***.

[75] **FIG. 8** is a diagram of an image-beam generator ***800*** that incorporates the beam combiner ***500*** of **FIG. 5** according to an embodiment of the invention. As discussed above in conjunction with **FIGS. 3, 4**, and **5**, optical path length is approximated as actual path length in the following discussion. The image-beam generator ***800*** includes a beam source ***802***, which includes conventional single-pixel beam generators ***804***, ***806***, and ***808***, such as laser diodes or light-emitting diodes (LEDs), for respectively generating the R, G, and B beams ***102***, ***104***, and ***106***. As discussed above in conjunction with **FIG. 5**, the R and G beam generators ***804*** and ***806*** are each located a distance D from the beam input faces ***514*** and ***512***, respectively, and the B generator ***808*** is located D + 2W from the input face ***512***. The beam source ***802*** also includes drivers ***810***, ***812***, and ***814*** for respectively driving the beam generators ***804***, ***806***, and ***808***. The sources ***804***, ***806***, and ***808*** and the drivers ***810***, ***812***, and ***814*** compose the respective R, G, and B beam-generating sections of the beam source ***802***. The image-beam generator ***800*** may also include a heat sink ***816*** for dissipating heat generated by the drivers and beam generators, and includes an optical train ***818***, such as a lens, for generating an image beam ***820*** from the composite beam ***502***. For example, the train ***818*** may generate the image beam ***820*** by, *e.g.*, correcting for aberration of the composite beam ***502*** or focusing the composite beam. As discussed below in conjunction with **FIG. 9**, a scanner (not shown in **FIG. 8**) sweeps the beam ***820*** across a screen or one's retina to generate an image.

[76] In operation, the beam source ***802*** temporally modulates the intensities of the R, G, and B beams to change the color and other characteristics of the image beam ***820*** on a pixel-by-pixel basis.

[77] Alternate embodiments of the image-beam generator ***800*** are contemplated. For example, by modifying the locations of the R, G, and B beam

generators ***804***, ***806***, and ***808***, the generator ***800*** can incorporate the beam combiner ***300*** (**FIG. 3**) or ***400*** (**FIG. 4**) instead of the combiner ***500***. Furthermore, the beam generators ***804***, ***806***, and ***808*** can be modified so that they can generate the R, G, and B components of an entire image such that the beam ***820*** projects an entire image, not just one pixel of an image. In addition, the positions of the R and B generators ***804*** and ***808*** can be swapped as discussed above in conjunction with **FIG. 5**. Moreover, the beam source ***802*** may generate only one or two of the R, G, and B beams such that the image beam is monochrome or otherwise does not range over the full color spectrum.

[78] **FIG. 9** is a diagram of an image generator ***900*** that incorporates the image-beam generator ***800*** of **FIG. 8** according to an embodiment of the invention. In addition to the generator ***800***, the system ***900*** includes a conventional scanning mirror ***902***, such as a microelectromechanical (MEM) mirror that is operable to sweep the image beam ***820*** across a display surface such as a retina ***904*** to generate an image thereon. When the image generator ***900*** is used to sweep the beam ***820*** across a retina, it is sometimes called a virtual retinal display (VRD).

[79] In operation, the image-beam generator ***800*** directs the image beam ***820*** onto the mirror ***902*** via the optical train ***818***. The mirror ***902*** is operable to sweep the beam ***820*** through a pupil ***906*** and across the retina ***904*** by rotating back and forth about an axis ***908***.